POSSIBILITIES FOR LIMITING AIRCRAFT TURBINE ENGINE ABRASIVE WEAR OF INTERIOR DUCT ELEMENTS

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Summary

The paper describes the reasons for ingestion of contaminants into turbine engine interior with inlet air, resulting in lowered efficiency of main engine elements: compressor and turbine and further reduction of engine reliability and lifetime. The direct effect of the aerodrome (landing field) surrounding landscape on the type of contaminants ingested with the turbine engine inlet air and measures used to limit quantity of them are discussed in the paper. The inlet vortex is presented as the fundamental cause for turbine engine ingestion of contaminants from aerodrome surface, and analytic and experimental research methods used in investigation of this phenomena and preventive measures undertaken are also presented in the paper.

1. INTRODUCTION

The characteristic feature of internal combustion turbine engine in comparison with internal combustion piston engine is the four times greater inlet air ingestion for the same power output. It results from the necessity to limit the temperature of the turbine engine working media („dilution" of the combustion gases with the cool air), considering strength limitations of the used heat-resistant constructional materials.

In the single-spool jet engines and in the internal ducts of bypass engines, the composition of the combustion media is similar. However, the airflow in the external ducts of bypass engines is propelled by fan. In combat aircraft engines the airflow in the external duct is similar to the internal duct airflow. In passenger aircraft high bypass („fanjet") engines external flow rate is several times greater (5 to 8 times). For comparison, the 1000 hp piston engine needs only 1 kilogram of air per second, but similar power turbine engine uses as many as 4 kilograms of air per second. The 1000 daN thrust single-spool jet engine (e.g. SO -3 engine of the TS -11 „Iskra" aircraft) uses up to 18 kilograms per second of air, but the GE CF-6 bypass jet engine, (mounted on the PLL – LOT airline Boeing 767) during take-off needs up to 700 kilograms per second of air. Hence, even with the small amount of dust in environment, huge amount of contaminants can be ingested into the engine during take-off.

Type of airfield surrounding terrain, such as: existence of the rocky, sandy and dry type soils and existence of soil covering flora on the perimeters of taxiways and runways have the influence on the amount of dust and the type (hardness) of particles ingested into engine. The example of the quantitative mineralogical composition and the grain composition of dust originating from the areas of various soil types is shown on Fig. 1. The change of dust concentration in the function of the ag altitude is presented on Fig. 2.

The values of dust concentration due to the traffic in an airfield area are also variable but the course of these changes in function of the ag altitude is similar.

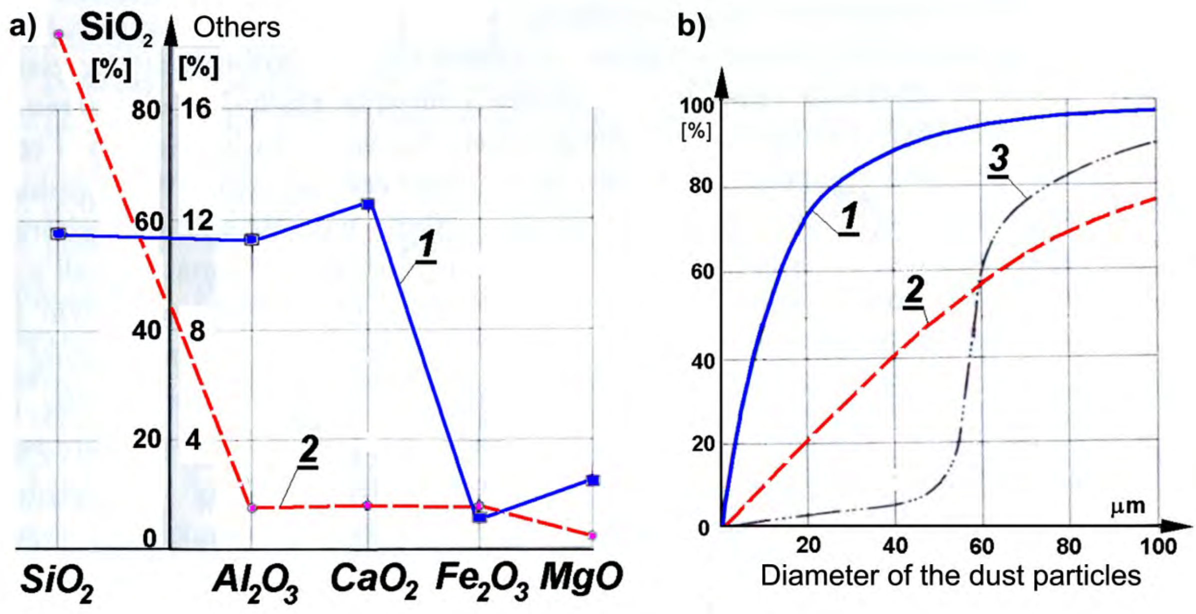

Fig.1. Dust composition
a) mineralogical (1 – from areas with the loess soil, 2 – from areas with the sandy soil,
b) granularity (1 – from areas with the loess soil, 2 – from mountain areas,
3 – from the Libya's Desert

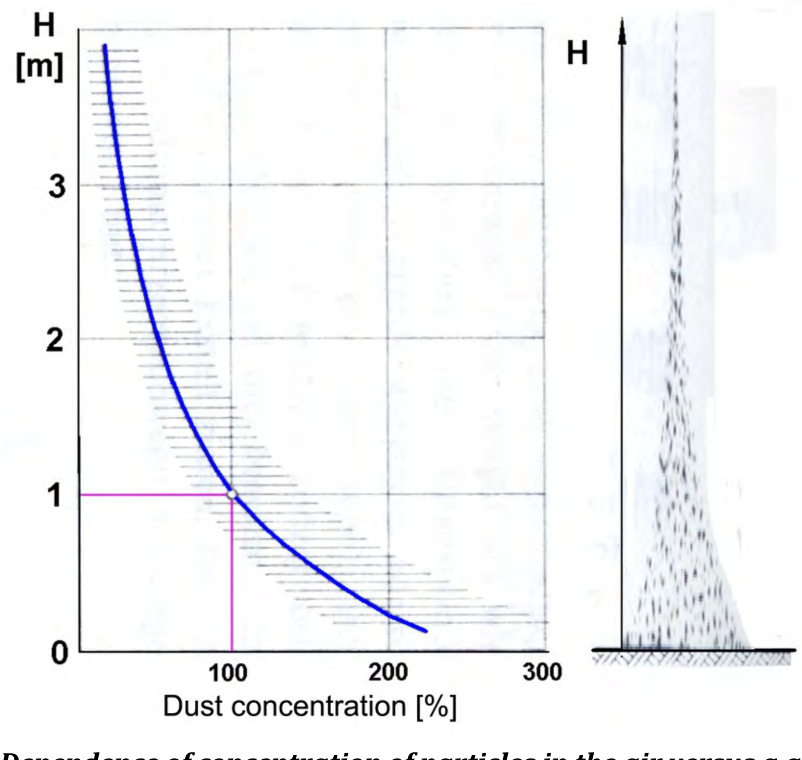

Fig. 2. Dependence of concentration of particles in the air versus a.g. altitude

The main reason for raise of dust particles from airfield pavement (particularly the larger sizes of particles) is airplane and helicopter propwash and the jet engine exhaust gas plume. So, this is absolutely necessary to watch and care for the pavement cleanliness in the airplane and helicopter take-off and landing areas, and the touchdown areas for thrust reversing airplanes. Considering that, the team take-offs are also dangerous for the engines.

Jet engine dense and intense inlet airstream favours creation of the inlet vortex, which – like the vacuum cleaner – sucks in (or even extracts from soil) the larger particles, which are dangerous for the engine structure. The intensity of created vortex depends, among others, on the engine inlet lip position (elevation) over the pavement. The occurrence of created vortex has the remarkably stochastic character, but the threat of engine damage and as well the threat to flying safety forces us to search methods to make vortex creation difficult.

Contemporary science allows one to find the root cause of vortex creation, both theoretically and experimentally, and gives us the chance to limit its intensity.

2. ANALYSIS OF FLOW LINES IN FREE AIRSTREAM TO ENGINE INLET

The Boundary Element Method (BEM) is particularly useful to research the phenomenon of jet engine inlet vortex and its creation favourable (or unfavourable) conditions. This method makes possible to determine the course and distribution of flow lines in the surrounding half space in front of the engine inlet [2]. In the older textbooks, flat (two dimensional) model of flow lines distribution was usually presented. Contemporary computer programs allow for quickly obtaining the results based on the three-dimensional model, which considers not only the influence the aerodrome pavement surface, but also the influence of the aircraft fuselage and the location of aircraft wing relative to the engine inlet.

Fig. 3 shows the distribution of flow lines in the engine inlet airstream (determined from two-dimensional, flat model) with influence of aerodrome surface for the given placement and size of the engine inlet [1]. One, the most important result of the distribution of airflow lines analyses is position determination of so-called stagnation line with its footing on the pavement surface, in place from which the airflow stream lines „are going out perpendicularly" and to which next to pavement surface airflow stream lines are directing radially, and raise together next, evenly distributed and enter engine inlet duct.

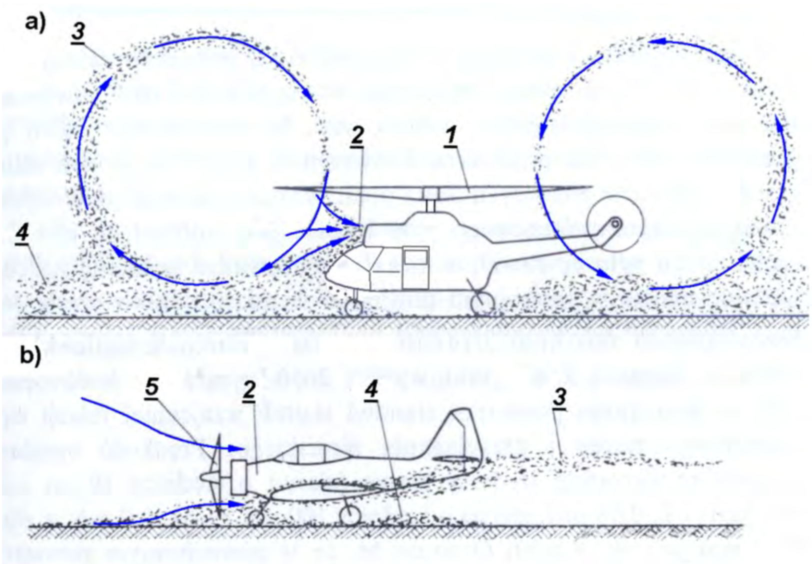

Fig.3. Dust lift-up from pavement during take-off a) helicopter, b) propeller-driven aircraft (1 – rotor, 2 – engine inlet, 3 – fine-grained dust, 4 – coarse-grained dust, 5 - propeller

The particular significance has the so-called stagnation line, clearly marked on Fig. 4, since the inlet vortex is created around it and ingests (like cyclone) all loose-laying or easily separated particles from pavement surface into engine interior.

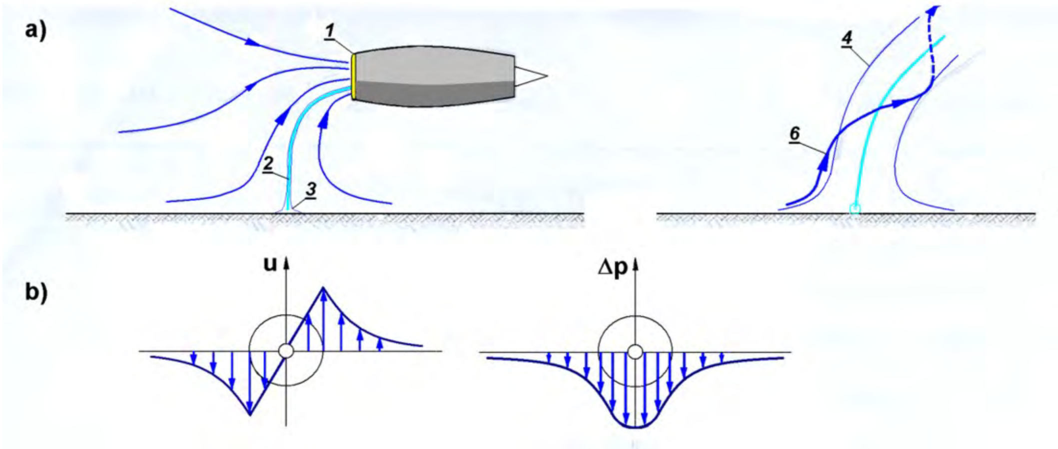

Fig.4. Distribution of engine inlet airflow stream lines with the influence of aerodrome pavement surface: a) end view, b) top view (1 – engine inlet, 2 – stagnation line, 3 – vortex footing, 4- vortex pipe, 5- air with dirt particles inflow directions, 6 – trajectories of dirt particles carried by inlet vortex

Fig. 4 shows in two projections so-called vortex pipe and the movement lines of small stones picked up from pavement and the distribution of airstream circumferential speed in the vortex pipe and outside space. The largest circumferential speed occurs on surface of the vortex pipe, and it sometimes achieves value close to the translatory speed of the engine inlet airstream. The strong negative pressure formed in the vortex pipe together with the gas-dynamic action of directed speedy airstreams carry away (and sometimes tear-out) particles of dust, gravel or concrete fragments of pavement surface and ingest them into engine ducts. The smaller particles settle on duct surfaces: compressor, combustion chambers and turbine, creating the caked deposits which alter the character of boundary layer flow and make heat transfer between gas stream and the construction elements difficult, leading to lowering elements efficiency and in the long run of exploitation creating permanent deformations and the cracks in engine construction elements. The general way to counteract the deposits grow is the engine duct washing (during engine cold crank) by injection of properly prepared liquid mixtures.

The larger particles ingested into the engine inevitably lead to permanent damage, like: tarnishing and scratching on the compressor and turbine blades, snatching pieces of material and bending the whole blades or their trailing edges. The only way to limit occurrence of such damages is assurance of the pavement surface durability and absolute cleanliness in takeoff start runway areas and thrust reverser usage areas and also in engine test areas.

Observations of airplanes during take-off in low temperature, high humidity conditions (vortex pipe surface with condensing water vapour is then clearly visible) confirm results of theoretical investigations presented above (see Fig. 5). Theoretical analysis of preceding engine inlet flow field distribution allows for investigation for routes of stream lines not only for case of stationary aircraft in stationary atmosphere, but also for the conditions of airplane movement during take-off acceleration. Fig. 6 shows shape of stagnation line for conditions, considered here. This analysis shows that during airplane movement, stagnation line „hides” under engine nacelle, and above specific, border speed V_{gr} stagnation line losses contact with aerodrome pavement and inlet vortex vanishes.

Fig. 5. Photo of inlet vortex, taken during engine ground test (Rolls Royce Trent 560 engine on Airbus 340-600 airplane)

In Poland, studies and experiments on conditions for inlet vortex creation and its possibility for ingestion of considerable mass of dust particles were performed in second half of seventh decade of twentieth century in Air Force Institute of Technology (R. Szczepanik) [14, 15, 16, 17, 18, 19] and were continued from beginning of eight decade in Institute of Aviation (L. Madej) [9, 10] on new combat-trainer aircraft.

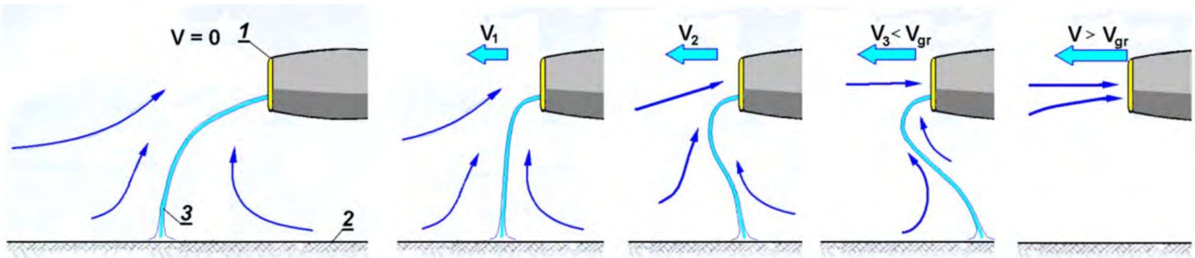

Fig. 6. Changes in shape of the stagnation line during airplane take off: 1 – engine inlet, 2 – pavement surface, 3 – stagnation lines,
$V_1<V_2<V_3<V_{gr}$ – airplane local velocities on the runway, relative to the stationary air.

In the same period, laboratory experiments with air mass flow approaching 2 kilograms per second on several models of various airplane engine air inlets were performed in Military University of Technology (WAT).

Publication of analytical investigations and results of experiments, together with Authors notices would be very helpful to aircraft designers and users, and also to the airport builders and airport services responsible for their technical state and cleanliness.

3. AIRCRAFT ENGINE PROTECTION AGAINST EROSIVE WEAR

Current manufacturing methods practically provide sufficient protection against corrosion of elements mounted in engine ducts and flowed around by air and combustion gases.

Materials with proper hardness and surface hardening by various enamel coverings are also used. In helicopter and propeller engines problem of inlet air filtration (dust particle removal) have not been sufficiently solved yet. Improvement of inertial air cleaners used on helicopters (radial, axial – radial and MultiCyclone) aimed at increase of dust removal efficiency and lowering flow resistance is performed continuously by manufacturers. One can expect application of these devices to inlets of propeller engines.

In military jet aviation, one can find the special inlets with movable ducts, being opened at the beginning of the take-off run, as they avert ingestion of dust particles from aerodrome pavement into engine. Characteristic design example, presented here on Fig. 7 are MiG-29 fighter aircraft engine inlets. During aerodrome movement - taxiing and take-off run, the air is taken from top wing area and classic ram air dynamic pressure engine inlets are used in flight.

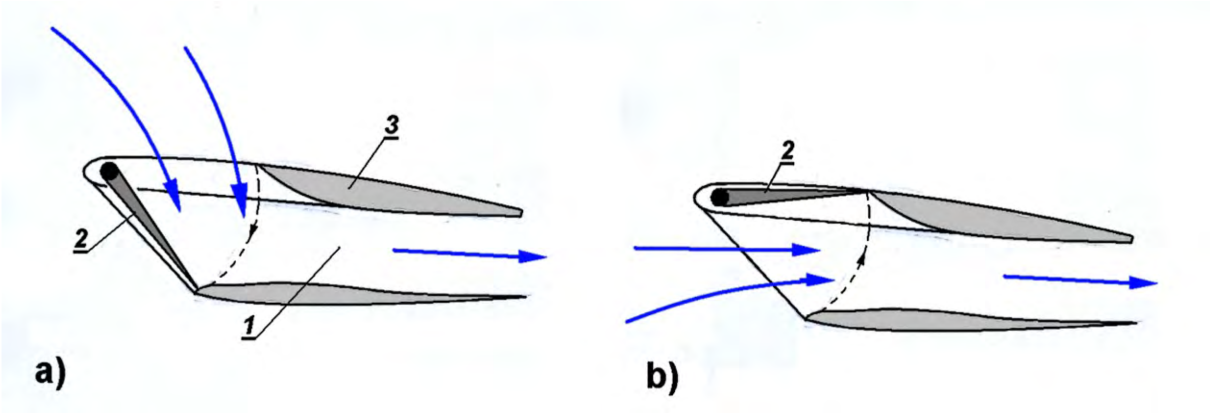

Fig. 7. Inlet air path to engines of the MiG -29 fighter aircraft:
a) during taxiing and take-off run, b) in flight
(1 – engine inlet duct, 2 – movable inlet flap valves, 3 – aircraft wing)

In significant number of aircraft types, like Yak-42 civil transport or Fairchild Republic A-10 Thunderbolt II combat strike aircraft, engines are mounted on rear fuselage side pylons, which don't limit creation of the inlet vortexes, but vortex foot places itself not on the aerodrome pavement surface, though on the upper wing surface, free from dust (Fig. 8a).

However, one doesn't find formation of inlet vortexes and engine ducts contaminants damages in middle engines, mounted above rear airplane fuselage (McDonnell Douglas DC-10 or Tupolev 154). Fuselage forms the obstacle, which precludes inlet vortex formation. Placement of the engine inlets high above pavement surface also has substantial meaning to the limitation of the conditions for inlet vortices formation (Ilyushin IL-62 aircraft). It also shows that screening of the engine inlets for reducing aircraft radar signature (like Northrop Grumman B-2 Spirit airplane) is simultaneously radical way for limiting possibilities of inlet vortices creation and contaminants ingestion from pavement surface.

Requirements to, so called engine service compliance (e.g. possibility for eventual adjustments with engines mounted on the airplane) are fulfilled easily when engines are mounted on the airplane on relatively lower level. Service tasks are easier to perform when service personnel have direct access to the engine from the ground surface. The rules for durability and cleanliness of airport pavement surfaces have to be sharpened (and compliance to them strictly executed) in places designated for performing engine maintenance and tests. In such cases, stationary methods for prevention of inlet vortexes creation are used.

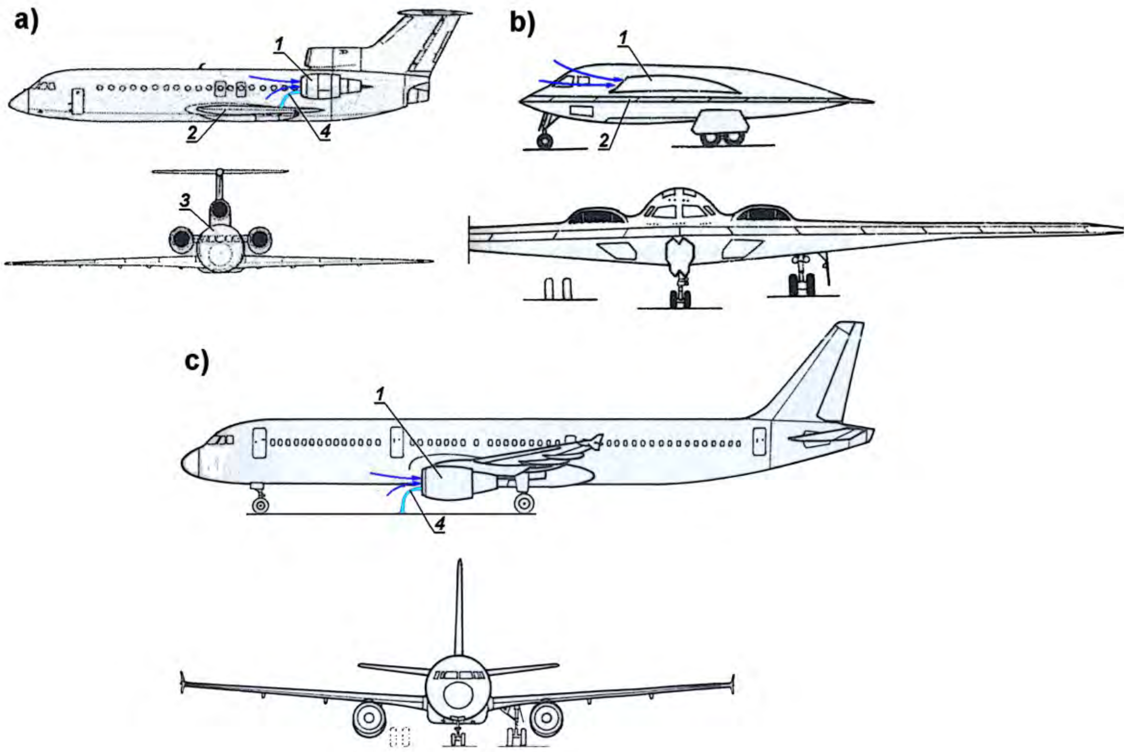

Fig.8. Jet engine placement in relation to the airplane fuselage and wing surface:
a) placement precluding dust ingestion from pavement surface (Yak-42 airplane),
b) placement precluding inlet vortex creation (B-2 airplane),
c) placement allowing inlet vortex formation (Airbus A 321 airplane),
(1 – engine, 2 – aircraft wing, 3 – aircraft fuselage, 4 – stagnation line)

Independently from shape of engine air inlet front lip, during engine start and ground run, inlet vortex can be eliminated by covering the stagnation area on the ground (foot area of eventual inlet vortex) by conical or pyramid solid. The same effect can be obtained by covering stagnation area by steel grating, made from flat, rectangular bars, positioned perpendicularly to the ground surface or even placing here sparse synthetic turf made from stiff fibers.

Figure 9 shows these methods, described previously, for inlet vortex elimination during ground engine tests. Flat bar depth or straw height above ground depends on engine inlet air steam intensity and distance from inlet lip to the airport pavement.

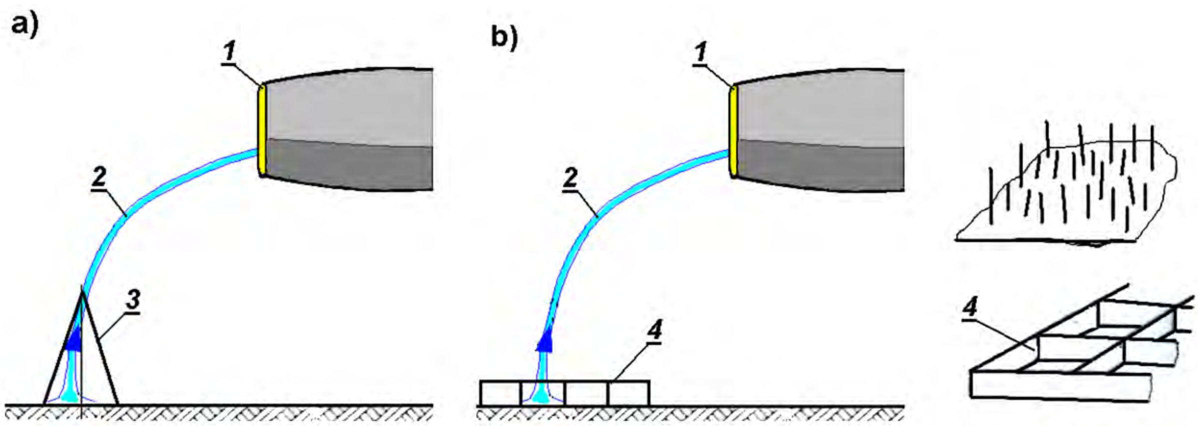

Fig. 9. Devices for limiting possibility of inlet vortex creation in ground engine test areas:
a) covering the stagnation line area with hindrance, b) covering of the stagnation point
(1 – engine inlet, 2 – stagnation line, 3 – conical or pyramid solid, 4 – flat hindrance)

Those devices cannot be used during airplane ground movements (eventually, artificial grass only). For moving airplane conditions, devices had to be mounted on aircraft structure. Figure 10 shows schematics of devices which totally preclude formation of the input vortexes (devices on Figs. 10a and 10c) or are precluding creation of vortexes with its feet on the ground (devices 10b and 10c) [2]. The basic fault of these devices is necessity of hiding them into the aircraft aerodynamic contour during the flight

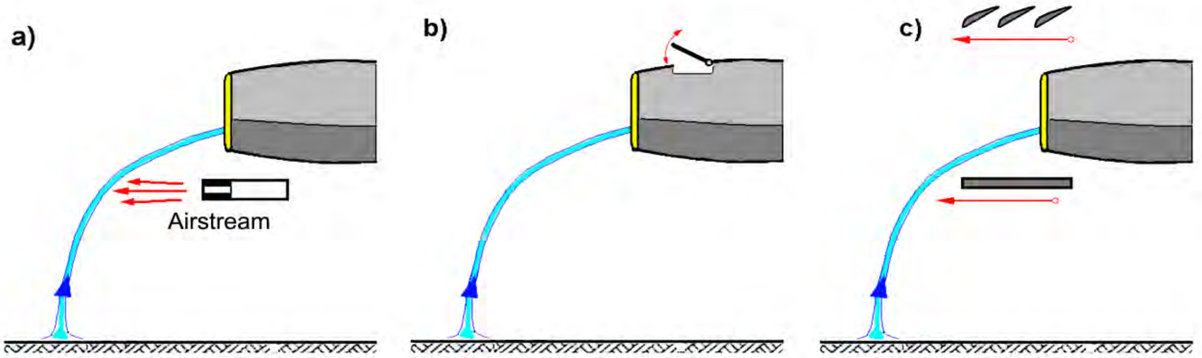

Fig. 10. Aircraft mounted devices for limiting possibilities of inlet vortex creation during ground movement a) blow nozzles, b) additional blow-in doors (side blow-in or upper blow-in doors), c) extendable plate or shutters, crossing stagnation line or inlet air stream

However, neither of these devices cannot protect against casting into engine inlet concrete particles or other contaminants by undercarriage wheels or exhaust nozzle jets of taking-off, preceding aircraft. Because of this fact, it is advisable to avoid team takeoffs, but it refers mainly to the military aircraft.

In case of vertical take-off and landing airplanes, reflowing exhaust jet of lifting engine nozzle gases blows off eventual inlet vortex foot from take-off pavement.

4. SUMMARY

Engineering design of contemporary airplanes and helicopters and their onboard equipment systems becomes even more and more complicated, delicate structurally, susceptible to mechanical failures and even more and more costly. Durability and reliability requirements are rising, also for lowering negative environmental influences (noise and pollution). One is forced to continuously improve design, manufacturing and assembly processes and construction materials. Continuously improved exploitation and technical state diagnostics methodologies have enormous influence on increase of engine durability. Automated engine control and state monitoring allows for engine preflight check test run elimination (including acceleration and deceleration tests) what splendidly lowered fatigue cycle wear and also fear for possibility of damages by contaminants, ingested in places designated to performing these tests.

Introduction of the engine interior ducts washing procedures into exploitation processes allows keeping engines at high level of efficiency for the long time. It results in high volume fuel savings in civil aviation (and is limiting emission of carbon dioxide into the atmosphere).

Experience, gathered during domestic exploitation of turbine engines and referring to their damages by ingested air dust particles, allowed to discover that even big particles „sucked in" through inlet vortex are colliding with inlet fan and compressor rotor blades at a distance equal to ¼ ... ⅓ of their blade length from the blade tip, similarly like the birds bodies ingestion collisions. It means that compressor, turbine and combustor elements placed in interior contour of twin flow engine are less susceptible to damages than elements in exterior contour.

The necessity of permanent investigations results from findings mentioned above, both experimental for currently exploited airplanes and theoretical, with modeling, for future airplanes. In creation of computational models one should consider influence of direction of rotation of fan or first compressor stage, velocity field of surface wind around airplane (in the area of possible vortex foot creation), and even influence of direction and value of Coriolis acceleration – depended on airport geographical coordinates. The cost of these investigations will be balanced, if owing to them costs of engines repairs or exchanges (equal to purchase) will be avoided, and to start with if flying safety will be preserved, without damages caused by ingested contaminants from airport pavement.

In the event of undertaking such investigations, one sees the necessity for their unification, at least in the areas of standard dust and contaminants definitions and model investigations of engine air inlet shapes and ducts, their placement on the airframe (inlet lip height above ground) and also application of equipment for elimination of inlet vortex creation possibilities.

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MOŻLIWOŚCI OGRANICZANIA EROZYJNEGO ZUŻYCIA ELEMENTÓW SKŁADOWYCH KANAŁÓW PRZEPŁYWOWYCH LOTNICZYCH SILNIKÓW TURBINOWYCH

Streszczenie

W opracowaniu opisano przyczyny przedostawania się zanieczyszczeń do wnętrza silników wraz z powietrzem wlotowym oraz wynikające stąd skutki w postaci zmniejszenia sprawności głównych zespołów: sprężarki i turbiny, a także ograniczenia niezawodności i trwałości silników. Omówiono wpływ bezpośredniego otoczenia lotnisk (lądowisk) na rodzaj zanieczyszczeń i sposoby ograniczania ilości zanieczyszczeń w strumieniu dolotowym silników turbinowych. Przedstawiono wir wlotowy jako podstawową przyczynę zasysania zanieczyszczeń z płyt lotniskowych przez silniki odrzutowe, a także analityczne i eksperymentalne metody badania tego zjawiska oraz sposoby utrudniające jego powstawanie.

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ВОЗМОЖНОСТИ ОГРАНИЧЕНИЯ ЭРОЗИОННОГО ИЗНОСА СОСТАВНЫХ ЭЛЕМЕНТОВ КАНАЛОВ ТЕЧЕНИЯ АВИАЦИОННЫХ ГАЗОТУРБИННЫХ ДВИГАТЕЛЕЙ.

Резюме

В разработке описаны причины проникновения загрязнений внутрь двигателей с засысаемым воздухом и вытекающие отсюда последствия, вызывающие уменьшение коэффициента полезного действия главных узлов: компрессора и турбины, а также ограничения надежности и прочности двигателей. Обсуждено влияние непосредственно окружающей среды аэродромов (посадочных площадок) на тип загрязнений и способы ограничения их количества в потоке засасываемом газотурбинными двигателями. Представлен входной вихрь как основная причина засасывания загрязнений с аэродрома реактивными двигателями, а также аналитические и экспериментальные методы исследования этого явления и способы затрудняющие его образование.